SUBMITTED TO APJ, 22 APRIL 2005
Preprint typeset using LaTeX style emulateapj v. 11/12/01

MESOLENSING EXPLORATIONS OF NEARBY MASSES: FROM PLANETS TO BLACK HOLES

ROSANNE DI STEFANO
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
Kavli Institute for Theoretical Physics, University of California Santa Barbara, Santa Barbara, CA 93106
Submitted to ApJ, 22 April 2005

ABSTRACT

Nearby masses can have a high probability of lensing stars in a distant background field. High-probability lensing, or mesolensing, can therefore be used to dramatically increase our knowledge of dark and dim objects in the solar neighborhood, where it can discover and study members of the local dark population (free-floating planets, low-mass dwarfs, white dwarfs, neutron stars, and stellar mass black holes). We can measure the mass and transverse velocity of those objects discovered (or already known), and determine whether or not they are in binaries with dim companions. We explore these and other applications of mesolensing, including the study of forms of matter that have been hypothesized but not discovered, such as intermediate-mass black holes, dark matter objects free-streaming through the Galactic disk, and planets in the outermost regions of the solar system. In each case we discuss the feasibility of deriving results based on present-day monitoring systems, and also consider the vistas that will open with the advent of all-sky monitoring in the era of the *Panoramic Survey Telescope and Rapid Response System* (Pan-STARRS) and the *Large Synoptic Survey Telescope* (LSST).

1. DETECTING MESOLENSING

The companion paper introduces the idea of mesolensing, in which a single lens has a high probability of producing a detectable event (Di Stefano 2006a). Nearby stellar remnants are examples of mesolenses. Consider, e.g., a neutron star located 100 pc from us, traveling with a transverse speed of 100 km s^{-1} in front of M31. Over the course of twenty to thirty years, the Einstein ring of the neutron star will traverse an area of roughly $0.02'' \times (4-6)''$. In most regions of M31, this area will contain several hundred stars. It is likely that one or more of these stars is bright enough that, when it is magnified, the integrated luminosity from a square arcsecond region around it will increase by 10%. During the same interval, there may also be several smaller magnifications, producing jitter in the baseline light. In addition, astrometric shifts of $\sim 0.001''$ may occur and be detectable in the images of several stars lying in an even larger swath across the sky. These lensing effects could potentially lead, through a monitoring program, to the discovery of a "new" neutron star, one whose presence is not yet known. Alternatively, if there is a known pulsar or X-ray emitter along the direction to M31, the region behind the mass can be targeted for repeated deep, high-resolution observations. Such observations would have the potential to measure the mass of the neutron star, determine its proper motion, and probe for evidence of companions.

This type of argument can be applied to other dark and dim masses located within roughly a kpc, ranging from the relatively rare isolated black hole, to the more ubiquitous low-mass dwarfs. If the lensing action of such objects can be detected, gravitational lensing will become a valuable tool to discover a larger fraction of them and to study their properties, including their masses and multiplicities.

1.1. *Plan of the Paper*

The primary goal of this paper is to study applications of mesolensing. We focus exclusively on photometric effects, although astrometric effects are also expected. The necessary background is covered in §2. Section 3 focuses on computing the event rates due to nearby stars: low-mass dwarfs, white dwarfs (WDs), neutron stars (NSs), and black holes (BHs). These forms of matter are known to exist. The predicted rates are high enough to provide a guaranteed signal in past, ongoing, and future monitoring programs. This signal can be used to study these nearby populations in a way that has not so far been possible. Even if the primary goal of a monitoring program is to study dark matter, the signal due to nearby masses must be identified so that events due to nearby lenses can be subtracted from the total lensing signal to determine the true contribution of other lens populations, such as MAssive Compact Halo Objects (MACHOs).

In §4, attention turns to forms of nearby matter for which there is as yet no direct evidence. Specifically, we consider (1) intermediate-mass black holes (IMBHs), (2) disk dark matter in the form of free-streaming planet-mass objects, and (3) possible planets in the outer regions ($>$ 1000 AU) of the solar system. Section 5 is a summary of the conclusions.

2. BACKGROUND ON MESOLENSING

Lensing events have been discovered by monitoring programs, each of which regularly observes a dense background field at intervals of one to several days. Attention so far has focused on the Galactic Bulge and the Magellanic Clouds. M31 has also been subjected to regular monitoring. The monitoring programs are designed to discover evidence of lensing by masses lying in front of the background; the presence of the specific masses that eventually produce events is not generally known prior to the observations. Monitoring observations can therefore discover and probe the properties of a population of dark or dim objects.

The monitored field can be viewed as a composite of many small subfields, each with linear dimensions θ_{mon}, where the value of θ_{mon} has typically been on the order of an arcsecond. The term "monitored region", for a specific lens, refers to a box centered on the lens with area $\theta_{mon} \times \theta_{mon}$. It was necessary to develop a mode of analysis that considers monitored regions, rather than individual stars, because the dense fields we observe always have multiple stars within each resolution element (Di Stefano & Esin 1995). Although the details of the analysis can be complex, the basic idea is that the image of the region obtained at time t is compared with an appropriately averaged image of the field, and differences are identified. The

value of this difference imaging approach is that variations of an individual star can be discovered, even when the field is so dense that the lensed star itself cannot be imaged by the telescope used for monitoring (see, e.g., Alard & Lupton 1998).

2.1. *Detectable Photometric Events*

Fractional increase in the amount of light received: In order for a photometric deviation above baseline to be detectable, we must receive an additional amount of light per unit time from the region, producing a fractional change of at least f_T. Typical values of f_T used so far in monitoring programs have been in the range $0.1-0.5$.

Distance of closest approach: Let the index i label an individual source star that lies close to the path of the lens. If the approach between this source and the lens is to produce a detectable photometric event, the required angular distance of closest approach is $\theta_{b,i}$. Because it is convenient to express angles in terms of the Einstein angle of the lens, we define $b_i = \theta_{b,i}/\theta_E$. If an individual star must experience a magnification $>> 1$ in order for the magnification of the monitored region to be $(1+f_T)$, then

$$b_i = \frac{L_i}{\langle L\rangle}\,\frac{1}{f_T N_{mon}} \tag{1}$$

This limit of small b_i is the limit used to compute the event rates presented below. It is possible, however for b_i to be even larger than unity. If, e.g., a single bright star is the dominant source of light in the monitored region, then $b_1 = 1, 2.8, 3.5$ corresponds to f_T approximately equal to $0.34, 0.02, 0.01$, respectively.

Event Duration: For point-source/point-lens events, the event duration is the only measurable parameter related to the lens mass. The Einstein crossing time is

$$\tau_E = \frac{2\,\theta_E}{\omega}$$

$$= 35\mathrm{days}\left(\frac{M}{1.4\,M_\odot}\right)^{\frac{1}{2}}\left(\frac{100\,\mathrm{km\,s^{-1}}}{v_T}\right)\left[\frac{D_L}{100\,\mathrm{pc}}\,(1-x)\right]^{\frac{1}{2}} \tag{2}$$

The measurable duration of an event is $b_i\,\tau_E$.

Background field: We parametrize the source density in terms of an angle θ_1, the average angular separation between sources in the background field.

2.2. *Event Rates*

The rates of and characteristics of detectable photometric effects of mesolensing depend on the method of detection and on the physical parameters of the lens and of the background source field. The rate of events caused by an individual lens of mass M, located a distance D_L from us, lensing a source located at a distance D_S ($x = D_L/D_S$) is given by the expression below (Di Stefano 2006a). In this expression θ_E represents the Einstein angle, and ω is the relative angular speed between the lens and source. For nearby lenses, ω is almost exactly equal to the angular speed of the lens with respect to Earth.

$$\mathcal{R}_1^{detect} = \frac{2\,\theta_E\,\omega}{f_T\,\theta_{mon}^2}$$

$$= \frac{0.021}{\mathrm{yr}}\left(\frac{0.1}{f_T}\right)\left(\frac{1''}{\theta_{mon}}\right)^2\left|\frac{\hat{\mathbf{v}}_\mathbf{L}}{100\mathrm{kms}^{-1}}+\frac{\hat{\mathbf{g}}}{5}\right|$$

$$\times\left(\frac{M}{0.35\,M_\odot}\right)^{\frac{1}{2}}\left(\frac{100\mathrm{pc}}{D_L}\right)^{\frac{3}{2}}(1-x)^{\frac{1}{2}} \tag{3}$$

The transverse velocity of the lens is represented by $\hat{\mathbf{v}}_\mathbf{L}$, and the effects of the Earth's motion are incorporated by the vector $\hat{\mathbf{g}}$, whose direction depends on position relative to the ecliptic and whose magnitude is of order unity. The validity of this expression requires that the background field is dense enough that the monitored region ($\theta_{mon}\times\theta_{mon}$) is likely to contain stars. Note that the value of R_1^{detect} increases as θ_{mon} and f_T decrease.

The total rate of detectable events for a population of lenses, each with mass M, can be written as follows, where we assume that $x << 1$. Ω_{gal} is the surface area of the galaxy expressed in square degrees. We assume that the density of potential lenses is constant.

$$\mathcal{R}_{tot}^{detect} =$$

$$\frac{13.5}{\mathrm{yr}}\,\frac{\Omega_{gal}}{\square^o}\left(\frac{0.1}{f_T}\right)\left(\frac{1''}{\theta_{mon}}\right)^2$$

$$\left(\frac{N_L}{0.1\mathrm{pc}^{-3}}\right)\left|\frac{\hat{\mathbf{v}}_\mathbf{L}}{100\mathrm{kms}^{-1}}+\frac{\hat{\mathbf{g}}}{5}\right|$$

$$\times\left(\frac{M}{0.35\,M_\odot}\right)^{\frac{1}{2}}\left(\frac{D_L^{max}}{\mathrm{kpc}}\right)^{\frac{3}{2}} \tag{4}$$

2.3. *Light Curve Characteristics*

It might be supposed that, when the Einstein ring of the lens is large enough to encompass the positions of several source stars, multiple-source effects could be important. Indeed, as discussed below, in rare cases the presence of multiple sources produces distinctive signals. Nevertheless, most light curves caused by nearby lenses have the same functional form as light curves caused by more distant lenses. This is because events in which there is a significant deviation above baseline tend to be produced by: (a) bright stars; it is not likely that there are two or more bright stars in any specific monitored region; (b) close approaches to an individual source star; it is even less likely that the positions of two bright source stars lie within a small fraction of an Einstein angle.

Against very dense source backgrounds, or if the observations are sensitive enough, the event rate can be so high that sequences of events are be caused by a single lens, particularly if the lens in near enough to have a proper motion of several θ_E per year. The likelihood of sequences of events increases with the value of $\theta_{b,i}/\theta_1$. Indeed, as the value of $\theta_{b,i}/\theta_1$ becomes as large as roughly 0.1, the probability that two or more stars will be detectable lensed simultaneously increases. The simultaneous lensing of two stars produces light curve shapes that differ from the standard Paczyǹski form, but which can nevertheless be well fit by a lensing model in which the event is produced by light from a small number of source stars.

2.3.1. *Wide-Field Monitoring Programs*

The event rate is proportional to the total area monitored. This means that wide-field monitoring programs can play an important role in detecting lensing. Within the next 5 to 10 years two wide-field monitoring projects will begin. Pan-STARRS, *Panoramic Survey Telescope and Rapid Response System*, will monitor the sky as seen from Hawaii, (Chambers te al. 2004) and LSST (the *Large Synoptic Survey Telescope*), will operate from Chile (Stubbs et al. 2004) . Together, these surveys will cover the sky. In addition, they will be able to achieve

smaller values of f_T than monitoring programs until now. As we will discuss in §3, the combination of wide-field coverage, good photometry, and high angular resolution will produce high event rates.

3. APPLICATIONS: NEARBY STELLAR MASSES

Nearby stellar populations provide a guaranteed reservoir of lensing events. While every nearby star lenses its background, it is easiest to detect lensing by objects that are dark or dim in those wavebands in which the background is bright. Optical monitoring programs are therefore sensitive to lensing by stellar remnants and by low-mass dwarfs. These are the lenses we consider in this section.

To compute the expected rate of lensing events caused by nearby stars against any specific background requires information about the spatial, mass, luminosity, and velocity distributions of the lenses. The same types of information are needed for stars in the source galaxy. The methods employed to detect and select events then determine the rate of detectable events. Given the complexity of the problem, we do not seek to compute rates with quantifiable uncertainties in this first analysis. We can, however, use known average properties of the source and lens populations, to make reasonable rate estimates by substituting appropriately into the formulae derived in paper 1 (Eqs. (3) and (4) here). This allows us to answer some general questions.

(1) What are the relative rates of events caused by different types of lenses? We know, e.g., that some M-dwarf events have been observed. How many such events must be observed before we are likely to detect lensing by a T dwarf? white dwarf? neutron star? black hole?

(2) Are the rates of events caused by nearby lenses high enough that we expect a significant number of them to be in the data sets of (a) completed, (b) ongoing, and (c) future monitoring programs?

3.1. *The Lenses*

3.1.1. *Stellar Remnants*

The local spatial density of WDs has been measured, We use $N_L = 6 \times 10^{-3}$ pc^{-3} (Holmberg, Oswalt, & Sion 2002; Kawka, Vennes, & Thorstensen 2004; Liebert, Bergeron, & Holberg 2005). In the calculations below, we have modeled the WD population with constant spatial density equal to this approximate locally-measured value. This is a reasonable approximation because the majority of existing WDs are descendants of old stellar populations and are therefore not expected to be confined to a thin disk. Nevertheless, we expect some decline in the number of hot young WDs with height above mid-plane, with thick-disk and halo WD populations becoming dominant with increasing height. If the Galaxy is modeled as a cylinder with radius equal to 12 kpc and total height equal to 2 kpc, a constant density of $N_L = 6 \times 10^{-3}$ pc^{-3} corresponds to a Galactic WD population of 5×10^9 WDs, with an estimated total mass of WDs of $3 \times 10^9 M_\odot$. We have checked that this number is reasonable by comparing it with the results of simulations we have conducted. Starting with a Miller-Scalo IMF, we find that the total mass in stars is roughly $5-10$ times larger than the mass in WDs, with the ratio depending on the age of the population. Since an estimate of $3 \times 10^{10} M_\odot$ is consistent with some observational estimates of the stellar mass of the Milky Way, but low for others, the density employed here does not overestimate the WD density. (See, e.g., Sakamoto, Chiba, & Beers 2003; Beers et al. 2005.) The masses of isolated WDs typically range upward from $0.5 M_\odot$ to close to the Chandrasekhar mass of $1.4 M_\odot$; We will use a single value, $0.7 M_\odot$.

For NSs we take $N_L = 6 \times 10^{-4}$ pc^{-3}, producing 5×10^8 Galactic NSs within 1 kpc of midplane. This is consistent with or lower than most independent estimates of the size of the NS population (see, e.g., references in Kaspi, Roberts, & Harding 2004). We take the mass of NSs to be $1.4 M_\odot$. For BHs we take $N_L = 6 \times 10^{-5}$ pc^{-3}, producing 5×10^7 Galactic NSs within 1 kpc of midplane. (This is smaller than the numbers often quoted; see, e.g. McClintock & Remillard 2003). We take the mass of BHs to be $14 M_\odot$.

3.1.2. *Low-Mass Dwarfs*

The low-mass dwarfs we consider are M dwarfs, L dwarfs, and T dwarfs. We have drawn the spatial densities for each of these classes, shown in Table 1, from the review by Kirkpatrick (2005), with input from Cruz et al. (2003), Reid, Gizis, & Hawley (2002), Knapp (2002), Kirkpatrick (2001b), Burgasser (2001), and Gizis et al. 2000. Note that L dwarfs appear to be relatively rare. This is because of both the shape of the initial mass function, and the fact that the transition from stellar to non-stellar objects occurs within the L-range, and old brown dwarfs will have had time to cool and will therefore drop from the class of L dwarfs and will appear instead as T dwarfs. Naturally each of these classes encompasses a range of masses. To simplify the calculations, however, we use a single mass for each class. For M-dwarf lenses we use $0.2 M_\odot$, for L dwarfs we use $M = 0.1 M_\odot$, while for T dwarfs we choose a sub-stellar mass of $0.05 M_\odot$.

3.1.3. *Flux from the Lenses*

Among the lenses, the intrinsic optical luminosity of NSs is low enough that they will not contribute significantly to light from the monitored region; the B magnitudes of the known isolated neutron stars tend to be in the range from 26.6 to 27.2 (Haberl 2005). Since isolated black holes have yet to be discovered, we don't know the range of optical luminosities, but the absence of radiation from a surface and the possible advection of energy through the event horizon suggests that they may be even fainter. This is not necessarily true for nearby WDs or cool dwarfs, especially if they are young. For example, cool dwarfs have been observed with absolute I magnitudes ranging from 12 to 22 (Dahn et al. 2002). Furthermore, variability has been observed (Bailer-Jones & Mundt 2001). This means that in some cases, light from a nearby lens may be the dominant source of variable light in the wavebands at which it is most luminous. When this is the case, present-day algorithms that select microlensing candidates can fail. Therefore, e.g., events caused by some nearby cool dwarf stars may not have been identified as lensing candidates. For the same reason, events caused by hot WDs may have been identified as lensing candidates only if they were monitored at relatively long wavelengths.

3.2. *Relative rates of detectable events for lenses of different types*

3.2.1. *Individual Lenses*

M-dwarf-lens events have been detected. It is therefore useful to compute the rates expected for other types of lenses, relative to the rate for M dwarfs. We first compare the rates for individual objects, using Eq. 3. For two objects located the

TABLE 1
EVENT RATES AND DURATIONS RELATIVE TO M DWARFS

Lens type	ρ (pc^{-3})	Relative value of $\mathcal{R}_1^{detect}$	Relative value of $\mathcal{R}_{total}^{detect}$	Relative event duration
L-dwarfs	2e-3	0.7	0.02	0.7
T-dwarfs	2e-2	0.5	0.17	0.5
White dwarfs	6e-3	1.7	0.17	1.7
Neutron stars	6e-4	13.	0.13	0.5
Black holes	6E-5	8.4	0.01	8.4

TABLE 2
RATES FOR DIFFERENT OBSERVING STRATEGIES

Lens type	**Past** per decade per $\square^o$	**Present** per decade per $\square^o$	**Future** per decade per $\square^o$	**Future** per decade **over 150** $\square^o$
M dwarfs	(0.3,0.8,2.2)	(5.7,16,46)	(110,320,920)	(1.7e4,4.894,1.4e5)
L dwarfs	(6.4e-3,1.8e-2,5.1e-2)	(0.13,0.38,1.1)	(2.7,7.6,22)	(400,1100,3200)
T dwarfs	(4.5e-2,0.13,0.36)	(1.0,2.7,7.6)	(19,54,150)	(2900,8100,2.3e4)
WDs	(5.0e-2,0.14,0.4)	(1.1,3.0,8.6)	(21,61,170)	(3200,9100,2.6e4)
NSs	(3.6e-2,0.1,0.3)	(0.76,2.1,6.1)	(15,43,122)	(2300,6400,1.8e4)
BHs	(2.3e-3,6.4e-3,1.8e-2)	(4.8e-2,0.14,0.38)	(1.0,2.7,7.7)	(140,400,1200)

The observing set up for (1) “past": $f = 0.34$;, $\theta_{mon} = 2.5''$; (2) “present": $f = 0.1$;, $\theta_{mon} = 1''$; (3) “future": $f = 0.02$;, $\theta_{mon} = 0.5''$. Each prediction consists of a triad of numbers, corresponding to three values of D_L^{max}: (250 pc, 500 pc, 1 kpc).

same distance from us, and monitored with the same observational set-up, the relative rate depends only on the ratio of the square root of their masses, and on the ratio of their transverse speeds. The results are shown in the third column of Table 1.

To compute these ratios, we have assumed that the transverse speeds of all M dwarfs, L dwarfs, T dwarfs, WDs, and BHs are the same. Observations of pulsars, however, clearly show that the typical speeds of neutron stars are higher, presumably due to kicks associated with the supernova explosions that spawned them. Although the initial velocity distribution of neutron stars is highly uncertain, one widely accepted model is that of Arzoumanian et al. (2002). The velocity distribution consists of two Maxwellians. One of these contains 40% of the neutron stars and is peaked at 127 km s^{-1}; the second, including the rest of the stars, is peaked at 707 km s^{-1}.) 15% of all neutron stars have speeds in excess of 1000 km s^{-1}. To take into account the relatively higher speed of NSs, we use for them a transverse speed that is five times larger than the transverse speeds used for the other stellar lenses. For this reason, Table 1 indicates that an individual NS lens can produce an event rate that is larger than that produced by a BH lens, even though the BH is more massive. The duration of the NS-generated events would tend to be shorter, however. On average, if we are monitoring a single lens, the time between events would be shortest for NS-generated events and longest for T-dwarf-generated events.

3.2.2. *Relative Rates in a Monitored Region*

If we are monitoring a large region, without prior knowledge of individual lenses in the foreground, we must use the expression for the total rate in Eq. (4), which includes the relative densities. The results for different stellar lenses, relative to M dwarfs, are shown in the fourth column of Table 1.

These results indicate that the ratio between the number of M-dwarf events and the total number of events caused by all other stellar lenses is roughly 2 to 1. If, therefore, there are even a modest number of M-dwarf lensing events in a data set, the data set is very likely to also include events caused by compact objects and by brown dwarfs. Note that we have assumed that the spatial distributions of these different classes of lenses are similar. If each population can be modeled by a spatial distribution that falls off exponentially with height from the Galactic midplane, and also with radial distance from the Galaxy center, then differences among the populations are quantifiable through differences among the exponents applicable for each population. When these population differences are integrated over a distance of a kpc, relevant for nearby lenses, they tend to change the relative results by a factor of at most a few.

3.3. *Event Rates*

Table 2 is designed to predict the rates of events caused by nearby lenses in optical monitoring programs of the past, present, and future. To generate the rates shown in Table 2 we used Eq. 4. We assume three different types of observational set-up. The set-up labeled “past" simulates the first generation of microlensing monitoring surveys. We take $f_T = 0.34$, and $\theta_{mon} = 2.5''$. “Present" labels the observational set-up that is similar to the one presently used to monitor M31. In this case, $f_T = 0.1$, and $\theta_{mon} = 1''$. The moniker “Future" refers to the type of monitoring that will be conducted with Pan-STARRS and LSST. Specifically, we take $f_T = 0.02$, and $\theta_{mon} = 0.5''$. In the second, third, and fourth columns of Table 2, we compute the rate per decade per square degree. In the fourth column, we compute the rate per decade per 150 square degrees. This angular area is a conservative estimate of the area of the sky over which the combination of Pan-STARRS and LSST will be able to discover lensing events.

Each entry of Table 2 consists of three numbers. The leftmost number, which is always the smallest, is the rate if D_L^{max} is 250 kpc. For the middle (rightmost) number, we have used $D_L^{max} = 500$ pc ($D_L^{max} = 1000$ pc).

Table 2 illustrates that improvements in the observational set up, specifically, lowering the values of f_T and θ_{mon}, can increase the event rate in a dramatic way. Even if the detection efficiency for microlensing is low, future monitoring programs will be capable of detecting large numbers of low-mass stars and stellar remnants. Existing data provide opportunities to check if these predictions are overly optimistic. We show below that the predictions of Table 2 are consistent with data from the Magellanic Clouds.

3.4. *The Large Magellanic Cloud*

3.4.1. *Existing Data*

The Large Magellanic Cloud has been and continues to be monitored by several groups. Here we will focus on the small set of events identified by the MACHO team through 5.7 years of monitoring. The MACHO team has identified a set of 17 candidate microlensing events candidates (Alcock et al. 2000). Of most interest to this paper, 2 events are now known to have been caused by nearby dwarf stars.

The predictions under the column labeled "Past" are most relevant to this data set. Because both M-dwarf lenses were located at distances close to a kpc, it seems reasonable to take D_L^{max} to be roughly a kpc. Using the appropriate entry in Table 2, we predict 17 events caused by M dwarfs within a kpc ($[2.2\,\text{events per decade per }\square^0] \times 5.7\text{years} \times 13.5\,\square^0$). The efficiency for detecting and identifying these events, *if they are identical with typical microlensing events*, is roughly 0.3 (Alcock et al. 2000). With this value of the efficiency, we expect in the MACHO data set approximately 5 identified events caused by nearby M dwarfs. This is consistent with the two M-dwarf-lens events identified. The actual efficiency for detecting lensing events caused by nearby lenses is likely to be even lower, because some nearby lenses may have been bright enough to produce chromatic effects which would have eliminated the events from consideration. It is certainly possible that additional M-dwarf events have been detected, but are not yet identified as promising lensing candidates. In addition, the data set could contain one or two events caused by either a compact stellar remnant or a T dwarf.

3.4.2. *Future Observations*

When LSST monitors the LMC, the parameters used in Table 2 for "future" observations will apply, at least to a large portion of the LMC. Specifically, LSST (1) will likely achieve values of f_T smaller than 0.02, and, (2) in a single observation, it will reach limiting magnitudes dimmer than 24, so that regions $0.5''$ on a side will contain mulitple stars that can be detectably lensed. Considering only the portion of the LMC that was monitored by the MACHO team, we multiply the values for $D_L = 1$ kpc in column 4 ("future") of Table 2 by 13.5, to predict that in this region alone, a decade of LSST observations will detect 1.2×10^4 M dwarf events, with another $\sim 6 \times 10^3$ events caused by other dwarfs and by stellar remnants, including ~ 1600 neutron star events and 100 black hole events.

It is interesting to note that, even if we make very conservative assumptions, the numbers of events generated by nearby lenses in future monitoring programs is guaranteed to be high. If, for example, the effective value of D_L is actually only 250 pc, four times smaller than seems consistent with the MACHO results, this would decrease the rate by a factor of only 8. If, in addition, the efficiency is 10%, which is lower than expected, nearby lenses would still produce a large number of events. For example, under these conservative assumptions, this limited portion of the LMC should, over a decade, exhibit 20 neutron-star generated events (150 M-dwarf-generated events), each potentially measuring mass and multiplicity. Considering the entire sky, the numbers increase by a factor of at least 10. Although assumptions like the ones we make in this paragraph are inconsistent with the MACHO LMC and OGLE Bulge results, and therefore lead to unrealistically small lower limits on the numbers of expected events, they nevertheless predict a significant number of mesolensing events.

Considering the LMC itself, area out to the D25 isophote is 6-7 times larger than the area monitored by the MACHO team. Nevertheless, the total event rate will not be larger by a factor this large because the area that will be added by LSST is generally less dense than the area originally monitored. This means that the effective value of θ_{mon} must be larger. With, e.g., $\theta_{mon} \sim 3''$, corresponding to roughly 65 stars in each the monitored region for a stellar density of 0.1 pc^{-3}, the added regions of the LMC would contribute roughly $1/6$ as many events as the central region. While the central region would dominate, the number of events detected against the outer portions of the galaxy is also large.

3.4.3. *Disk of M31*

M31 has been the subject of regular monitoring by independent teams during the past several years. Image differencing methods have been used to identify candidate microlensing events, using observing parameters f_T and θ_{mon} roughly comparable to those used in the row labeled "Present" in Table 2. The surface area of M31 lying within the D25 isophote is approximately a square degree. In one year of monitoring, we therefore predict $(1, 2.4, 7.2)$ events if D_L^{max} is $(250\,\text{pc}, 500\,\text{pc}, 1\,\text{kpc})$. If the effective total duration of past observations is on the order of a year, it is possible that some of the events detected have been caused by nearby lenses; direct detection of the lens, or a pattern of continued time variability consistent with sequential lensing of different source stars could provide definitive evidence. Given the crowding of stars in M31, and the photometric sensitivity of current observations, we expect that b_i for typical M31 events should be small, perhaps ~ 0.1. This means that event durations will be shorter than is typical against the much less crowded background of the Magellanic Clouds. It is therefore interesting that a large fraction of the candidate microlensing events are short, with durations as measured by the full-width half maximum (t_{FWHM}) smaller than 5 days. Paulin-Henriksson et al. (2003) report on 4 events, 3 of which have $t_{FWHM} < 2.2$ days; the fourth has $t_{FWHM} = 21.8$ days. de Jong et al. (2004) report on 14 microlensing candidates, 5 of which have $t_{FWHM} < 5$ days, one with $t_{FWHM} = 9.4$ days, and an additional six candidates with $t_{FWHM} < 30$ days. (See also Belokurov et al. 2005.)

Future Observations: More significant in the long term, however, is the potential of future programs to detect lensing against the background of M31. Pan-STARRS will monitor M31. In a decade of monitoring, data from $\sim 500^{+900}_{-300}$ events caused by nearby lenses should be collected. Even if the detection efficiency is only a few percent, lensing by more than a dozen M dwarfs will be identified, and a neutron star could be discovered. The higher event rate for lenses of all types is caused by the lower values of θ_{mon} and f_T that are possible with Pan-STARRS.

The Halo of M31: The wide-field element of Pan-STARRS

will also be important because it extends monitoring to the halo of M31. All other things being equal, the rate of events is proportional to the surface area of the background source field. The surface area of the halo of M31 is ~ 100 times larger than the surface area of the disk. On the other hand, the average density of stars in the halo is lower than in the disk. For low stellar densities, the rate of events can be computed by considering the rate at which bright background stars enter the Einstein ring of the lens. (See paper 1, Di Stefano 2005.) But it is also possible to use Equations (3) and (4) of this paper, as long as the value of θ_{mon} is chosen appropriately.

In order for the formalism that was used to derive these expressions to be applied, regions of size θ_{mon} must, on average, contain one or more source stars bright enough to produce a detectable baseline. For dense fields, the smallest such region is smaller than the smallest region the observing teams can monitor, based on present-day spatial rsolution and pixel sizes. That is, we are limited by present-day technology. For low-density fields, on the other hand, achievable values of θ_{mon} may be too small for a field of size $\theta_{mon} \times \theta_{mon}$ to contain bright stars. This doesn't mean that observers should degrade their resolution. Instead, if we want to use Eqns. (3) and (4) to compute event rates, we must use an effective value of θ_{mon}^{eff}, large enough to contain some source stars, and possibly larger than the actual values of θ_{mon} to be used in observations. The dependence of the rate on the source surface density then enters through the factor of $1/\theta_{mon}^2$, which should be replaced by $(\theta_{mon}^{eff})^2$. A lower limit on θ_{mon}^{eff} can be estimated by first computing θ_1, where $\sigma_S \theta_1^2 = 1$. In the disk of M31, if N_S is approximately 0.1 pc^{-3}, then $\theta_1 \sim 0.027''$. If the monitored field must encompass roughly 100 (10) stars in order for one of them to be bright enough to be detectably lensed, then $\theta_{mon}^{eff} = 10\,\theta_1 \sim 0.27''$ ($\theta_{mon}^{eff} = 3.2\,\theta_1 \sim 0.08''$). This verifies that, in the disk of M31, the lower limit on the value of θ_{mon} is at present determined by technical considerations, not by the density of stars. As we move outward from the center of the galaxy, we can continue to use values of $\theta_{mon} = 0.5''$ (θ_{mon} of $1''$) in regions with average stellar densities as low as 25% (6%) of the average disk density. This general argument simply points out that there can be a region surrounding the disk of the galaxy in which the rate of lensing events can be comparable to the rate in the disk.

Farther from the center of the disk, the value of θ_{mon} to be used in the calculations, θ_{mon}^{eff}, is determined by the local stellar surface density. If the average surface density of the major portion of the halo is 0.0001 stars pc^{-3}, θ_{mon}^{eff} would be $\sim 8.4''$, for regions containing 100 stars. Those source stars that can be detectably lensed in the halo will consist primarily of subgiants and giants. If this area of the halo covers an area equal to 100 times the area of that part of the disk with $\theta_{mon} = 0.5''$, then the rate of halo events will be 0.35 the rate of disk events.

Lensing of halo sources will produce hundreds of events per decade. The spatial distribution of the events, and the range of time durations as a function of position will map the density and luminosity distribution of halo stars.

3.4.4. *More Distant Galaxies*

As we look toward the disks of more distant galaxies, the intrinsic rate per lens is the same as for the disk of M31. This means that the total rate of detectable events scales as the projected area of the galaxy. At 10 Mpc, the area per galaxy is smaller by a factor of 100. On the other hand, if homogeneity is roughly correct, then an argument analogous to the one made in Olber's paradox, shows that the number of galaxies in equal-width shells at larger distances from us increases in just such a way as to keep the total area of sky (per shell) covered by galaxies the same. Our ability to detect events against the background of more distant galaxies is limited only by the facts that (1) the greater distance makes source stars in more distant galaxies appear fainter, while (2) there is a cut-off at the high end of the luminosity function. As we consider background galaxies at greater distances, the larger apparent magnitudes of even the brightest stars require smaller and smaller values of b_i. Consequently, the time durations of events decrease until they become impossible to observe.

Nevertheless, there is a large volume around us within which galaxies provide useful backgrounds for lensing by nearby stars. For example, the disks of galaxies other than M31 which happen to be located within 5 Mpc, but farther from us than 0.7 Mpc cover an approximately 3 square degrees of the sky (Tully 1988). In an all-sky monitoring program, the rate for the main body (excluding the halos) of external galaxies, could contribute several times more events than M31.

Just as the halo of M31 provides a background against which events can be detected, so do the halos of other external galaxies. As the distance from us increases, the ratio of the rate of lensing associated with the halo to that associated with the main disk of its galaxy will decrease, at least for late-type galaxies. This is because the brightest halo stars are likely to be low-mass giants, and they tend to be less luminous on average than the most luminous stars in young stellar populations.

3.4.5. *The ICM of Galaxy Clusters*

If a cluster at 20 Mpc has a radius of 1 Mpc, it subtends an area on the sky of roughly 25 square degrees. Most of that area is filled with the intracluster medium (ICM). Although not as dense as galaxies, the ICM can be a rich environment. The total light emitted by Virgo's ICM, e.g., is estimated to be $10-20\%$ of the light emitted by the cluster's galaxies (Feldmeier et al. 2004a, 2004b; see also Arnaboldi 2003, 2004). Comparing the ICM to a galaxy, there may be $10-20\%$ as many stars in a volume (surface area) 1000 (100) times greater.

The role of the ICM with respect to the galaxies in a cluster is analogous to the role played by the halo of M31 relative to the galaxy's disk. It is interesting that the distribution of stars in parts of Virgo's ICM has been observed to exhibit significant structure. *Over the long term, mesolensing observations could play a role in helping to map such structure by, e.g., studying how the event durations change with position.*

3.4.6. *All-Sky Monitoring*

The calculations above indicate that lensing events caused by nearby stars are present in existing data sets, and will be found in large numbers in the data sets collected by sensitive all-sky monitoring programs, such as Pan-STARRS and LSST. The durations will tend to larger than a few days, so the events will be discovered and the longer ones will be reasonably well sampled by the monitoring programs.

Lensing will therefore become a tool to discover very dim nearby stellar-mass and planet-mass objects. Under ideal circumstances lensing can also measure the masses of these objects, their proper motions, and provide information about multiplicity. This will lead to an unprecedented amount of information about stellar remnants and low-mass dwarfs, even

should detailed measurements be possible for only a subset of the events, e.g., those which are studied with "follow-up" observing programs that use more sensitive detectors and a higher sampling frequency.

As events are discovered over a large portion of the sky, we will learn about the background as well as about the lenses. This is because lensing can be detected across a wide range of background stellar densities. The spatial distribution of events and the distributions of event properties, especially the durations, can be linked to the density of the background field and can therefore be used to map the background.

4. APPLICATIONS: POSSIBLE LENSES

In this section the focus shifts to potential lenses whose existence has not been established. In these cases, mesolensing may provide a way to test for the presence of these objects and to either discover them or to derive upper limits on their populations.

4.1. *Intermediate-Mass Black Holes*

An increasingly active field of research is focused on so-called intermediate-mass BHs (IMBHs), with possible masses between roughly 50 and 10^5 solar masses (see, e.g., Miller & Colbert 2004). Although there is no direct evidence for IMBHs, increasing numbers of ultraluminous X-ray sources (ULXs) are being discovered in external galaxies (see, e.g., Mushotzky 2004). With X-ray luminosities typically between 10^{39} erg s^{-1} and 10^{41} erg s^{-1}, they are super-Eddington for $10\,M_\odot$ objects, suggesting that more massive compact objects, almost certainly BHs, may exist. If this interpretation of the evidence is correct, then the IMBHs in ULXs must represent a tiny fraction of all IMBHs. Most IMBHs may not be in binaries, and those that are may not be X-ray active at present. Those that are X-ray active are not likely to be in a ULX state. Detailed population estimates have not yet been made. The presence of IMBHs is also consistent with theoretical considerations suggested by the presence of supermassive BHs in galaxy centers (see, e.g., Volonteri, Madau, & Haardt 2004; Islam, Taylor, & Silk 2004 and references therein) and by the evolution of massive young star clusters (see, e.g., Portegies Zwart et al. 2004; Freitag et al. 2005 and references therein). If IMBHs exist, can they be observed against the background of M31 or other stellar fields?

If there are 10^7 IMBHs in the Galaxy, then, if the Galactic volume is approximately $300\,\mathrm{kpc}^3$, there is roughly 1 IMBH per kpc^3 per square degree. This corresponds to a spatial density of roughly 3×10^{-6} pc^{-3}. There may therefore be one IMBH lying in front of the main disk of M31, ~ 20 lying over the densest region of the LMC, ~ 100 in total in front of the LMC, and at least ~ 200 in front of the regions in which Pan-STARRS and LSST will find the most lensing events.

The question is then, whether we are likely to have detected lensing by IMBHs. Consider a lens with mass $M = 1400\,M_\odot$. If there are no other modifications to Eq. (3), then $\mathcal{R}_1^{detect}$ is 1.33 yr^{-1}. The true rate will be lower however, because D_L will, on average, be greater than 100 pc. Taking D_L to be 500 pc, we find $\mathcal{R}_1^{detect} = 0.12$ yr^{-1}. Even this is likely to be too optimistic, since the appropriate value of f_T for existing data is more likely be ~ 0.34, rather than 0.1; this reduces the value of $\mathcal{R}_1^{detect}$ to 3.5×10^{-2} yr^{-1}. The event time duration (with $D_L = 500$ pc is $b \times 6.8$ yr. This resulting duty cycle yields a 24% chance that any individual IMBH will serve as a lens. With, e.g., roughly a dozen IMBHs lying in front of the LMC, and a similar number in front of the Bulge along Baade's window, there is a chance that lensing by an IMBH has been observed.

The probability of detecting lensing caused by an IMBH will be significantly increased with the advent of Pan-STARRS and LSST. With f_T decreased to ~ 0.02, the value of $\mathcal{R}_1^{detect}$ increases from 3.5×10^{-2} yr^{-1} to 0.6 yr^{-1}. The time duration of events, which can then be followed to magnifications as small as 1.02, increases to $b \times 19.3$ yr. It therefore seems likely that an individual light curve will contain simultaneous signals of the ongoing lensing of several source stars. The signal will be complicated, but should be well-fit by lensing models. Failure to detect an appropriate signal with Pan-STARRS and LSST will allow us to place limits on the density of IMBHs with masses near $1000\,M_\odot$ of $10^{-8} - 10^{-7}$ pc^{-3}, and comparable limits even on BHs with masses of $\sim 100\,M_\odot$.

Once a region containing a possible IMBH lens is identified, it is possible that high-angular-resolution measurements will allow spatial effects associated with the lensing to be studied. In some cases (for the closest IMBHs or for those with masses $> 10^3 M_\odot$), the Einstein ring may be $\sim 0.1''$, making astrometric effects more accessible to measurement.

4.2. *Free-Streaming Dark Matter in the Solar Neighborhood*

The microlensing monitoring programs were able to place significant constraints on the fraction of the Halo comprised of compact objects in a variety of mass ranges. Below we show that monitoring programs should be able to detect or place limits on the presence of nearby compact objects. We don't know the underlying mass distribution of such objects, should they exist. We can, however, make assumptions about the range of possible masses, and determine which mass values would lead to detectable lensing signatures.

If, e.g., local dark matter has a density of 9×10^{-25} gm cm^{-3} (Gates, Gyuk, & Turner 1995), there could be roughly 100 Jupiter mass ($M = 10^{30}$ gm) objects within a pc of Earth. Their Einstein angles can be small.

$$\theta_E = 0.002'' \left[\frac{M}{10^{30}\mathrm{gm}} \frac{\mathrm{pc}}{D_L} (1-x) \right]^{\frac{1}{2}} \tag{5}$$

Nevertheless, finite source size effects should not interfere with detection when D_S is large. Indeed, θ_E would have to be $6 \times 10^{-7}{''}$ in order for the Einstein ring at the distance to M31 to be as small as $100\,R_\odot$. A more serious concern is finite lens size effects. Although dark matter may be transparent, the calculations will be altered if the mass distribution of the lens must be explicitly considered. If, however, the dimensions of the dark matter are similar to those of planets, finite lens size effects will be rare. [See Eq. (10).]

If these dark masses exist and if they are freely streaming through the Galaxy with typical velocities of 200 km s^{-1}, the angular velocities of those nearby can be large, as can the rate of events generated by a single such lens.

$$\omega = \frac{42''}{\mathrm{yr}} \left(\frac{v}{200\,\mathrm{km/s}} \right) \left(\frac{\mathrm{pc}}{D_L} \right) \tag{6}$$

$$\mathcal{R}_1^{detect} = \frac{1.7}{\mathrm{yr}} \left(\frac{0.1}{f_T} \right) \left(\frac{1''}{\theta_{mon}} \right)^2 \left| \frac{\hat{\mathbf{v}}_{\mathbf{L}}}{200\mathrm{kms}^{-1}} + \frac{\hat{\mathbf{g}}}{10} \right| \times \left(\frac{M}{10^{30}\mathrm{gm}} \right)^{\frac{1}{2}} \left(\frac{1\mathrm{pc}}{D_L} \right)^{\frac{3}{2}} (1-x)^{\frac{1}{2}} \tag{7}$$

The time duration per event is small.

$$\tau_E = \frac{2\,\theta_E}{\omega}$$
$$= 48\,\mathrm{min}\left(\frac{M}{10^{30}\mathrm{gm}}\right)^{\frac{1}{2}}\left(\frac{200\,\mathrm{km\,s^{-1}}}{v_T}\right)\left[\frac{D_L}{1\,\mathrm{pc}}(1-x)\right]^{\frac{1}{2}} \quad (8)$$

Note that, if deviations from baseline of 2% can be detected, the duration of an event can be 3 times longer–i.e., the time taken to cross 3 Einstein diameters. Given the fact that there is a distribution of velocities, and also a distribution of orientations, producing an even broader distribution of transverse velocities, we expect both shorter and longer events,

Because the Einstein ring is small, we are in the low-density regime, and events should primarily be single-source events. Nevertheless, as Eq. (7) indicates, sequences of events are expected because the angular speed is large.

The total rate per square degree is also high. Within 100 pc, there would be ~ 100 masses of 10^{30} gm per square degree.

$$\mathcal{R}_{tot}^{detect} = \frac{1130}{\mathrm{yr}}\,\frac{\Omega_{gal}}{\Box^o}\left(\frac{0.1}{f_T}\right)\left(\frac{1''}{\theta_{mon}}\right)^2 \left(\frac{N_L}{110\mathrm{pc}^{-3}}\right)\left|\frac{\hat{\mathbf{v}}_{\mathbf{L}}}{200\mathrm{kms}^{-1}}+\frac{\hat{\mathbf{g}}}{10}\right| \times\left(\frac{M}{10^{30}\mathrm{gm}}\right)^{\frac{1}{2}}\left(\frac{D_L^{max}}{\mathrm{kpc}}\right)^{\frac{3}{2}} \quad (9)$$

The duty cycle for events associated with these nearby lenses could be high enough to allow monitoring specifically designed to discover short-duration events to either discover or place limits on planet-mass, free-streaming dark matter.

If short-duration events are observed, and if the monitoring occurs regularly over the period of several years, several tracks of events should be observed. The number of tracks actually associated with lenses effect can be estimated through statistical simulations. Individual cases in which the tracks are reliably established as being caused by lensing will be important, because the distance to the lens and the lens may may be measured in such cases.

If no such events are discovered, limits on disk dark matter in the form of Jupiter-mass objects can be derived. Such limits on Halo dark matter are already strong, based on the EROS and MACHO data Alcock et al. 1998. Mesolensing observations, however, can place limits on disk dark matter. In addition, the limits can be placed on lower mass values. For lower-mass objects, the Einstein angle is smaller. This does not cause problems with finite source size, but it does decrease the time of events, making it more difficult to discover them. If, however, all of the dark matter is in the form of such low-mass objects, there will be more of them. This means that a larger number will be closer, so that the distribution of values of θ_E will still include some larger values. It also means that there will be a larger number of lenses with velocities directed along more radial paths, producing fewer events per year, but with each event having a longer duration than if the motion were perpendicular to our line of sight.

4.3. *Low-Mass Planets in the Outer Solar System*

We don't know whether the outer regions of our solar system, harbor planet-mass objects. At distances of ~ 1000 AU a planet would have to be far more massive than Jupiter, in order for its dynamical influence on the known outer planets to be discernible (Hogg et al. 1991). Mesolensing provides an independent way to derive limits.

It is possible, if a planet-mass object is close enough to us, for its angular size to be larger than its Einstein ring. The requirement that it fit inside its Einstein ring is:

$$\frac{D_L}{1000\,\mathrm{AU}} > 0.11\left(\frac{M_J}{M_p}\right)\left(\frac{R_p}{10^9\mathrm{cm}}\right)^2, \quad (10)$$

where M_p and R_p are the mass and radius of the planet, respectively. harbor planets comparable in mass

For a Jupiter-mass planet located 2000 AU from us, the size of the Einstein ring is roughly $0.02''$. For less massive planets, however, the Einstein angle can be in the milliarcsecond range (e.g., the Earth at 2000 AU) or even smaller. The event rate is high nevertheless, because the angular speed on the sky is high. A mass 2000 AU from us traverses an angle of approximately $200''$ every 6 months. If the Einstein angle is $0.02''$, the lens will move through ~ 5000 Einstein diameters in 6 months, and the Einstein crossing time will be approximately an hour. The area we will perceive the lens to cover across the source field per year is large: $4\,\Box''$ every 6 months.

The background field could be out of the ecliptic, because the distribution of outer solar system masses may be close to spherical. If such a planet, or planet exists, lensing by it is therefore most likely to be detected by wide-field monitoring programs like Pan-STARRS and LSST. The smaller values of f_T possible for these programs will also increase the rate at which any such planets cause events. Although the frequency of detected events and their durations will depend on the direction, there are important common elements across directions. First, events will be of short duration, typically hours or less. Second, individual lenses should each give rise to sequences of events. These sequences will trace the motion of the Earth, exhibiting a "forward" and "backward" motion every year. This back and forth swing will repeat on a yearly basis, with slight changes due to the relatively slow motions of the lens and background stars. It is important to note that astrometric effects can be significant as well, and may be studied with, e.g., Gaia (see Gaudi and Bloom 2005).

5. CONCLUSION

5.1. *Guaranteed Signal*

Discussions of "dark matter" typically focus on matter whose nature is yet to be understood. The local neighborhood is, however, filled with dark objects whose nature we think we understand (BHs, NSs, WDs, and low-mass dwarfs), but of which we have relatively few nearby examples. Mesolensing provides a way to conduct a census of such objects, providing mass estimates and distances for many, and opening the door to detailed study of some individual systems. Mesolensing observations are guaranteed to identify BHs, NSs, WDs, and low-mass stars within ~ 1 kpc of Earth.

The calculations of §3 indicate that events due to nearby lenses (1) should be part of virtually every microlensing data set collected so far, and that (2) wide-field monitoring programs will regularly discover signals due to nearby lenses; this provides additional motivation for Pan-STARRS and LSST. (3) A combination of programs will regularly discover BHs within a few kpc, as well as NSs and other objects of lower-mass.

5.2. *Tests for Exotic Matter*

Mesolensing can also discover or place limits on the existence of disk dark matter, and can contribute to surveys of the outermost regions of the solar system. Under certain circumstances it can be used to study more distant masses in binaries, possibly including intermediate-mass black holes in our own Galaxy and the supermassive black holes found at the centers of galaxies (Di Stefano 2007b).

5.3. *Pan-STARRS, LSST, and other monitoring programs*

One of the interesting results we have derived is the high rate of events possible with the coming generation of monitoring programs. Key factors in increasing the rate are the fact that sensitive photometry will allow smaller values of f_T, while better spatial resolution will allow smaller values of θ_{mon}, at least in fields crowded enough to contain stars in a surface area θ_{mon}^2. This means that the rate of events due to nearby stars per square degree will be significantly higher than at present. Pan-STARRS and LSST also naturally benefit from being able to monitor large areas. We have used what appear to be realistically achievable values of the parameters f_T and θ_{mon}. Even if the values eventually achieved are not optimal, the predicted rates are still high. The detection efficiency then determines the fraction of events that will be successfully identified. Detection efficiencies for past monitoring programs have typically been in the range of tens of percent. It is likely that new monitoring programs will be at least comparably efficient. Even though the cadences of wide-field monitoring may not be ideal for lensing, the greater photometric sensitivity means that events will typically last longer, providing more opportunities for detection. The upshot is that the predicted rate of events caused by nearby stars will be high enough to ensure that many nearby lenses will be detected, and some will be studied in detail.

It is interesting to note that, in general, we expect lensing events to be caused by nearby lenses, lenses in the background source field ("self-lensing") and possibly by MACHOs. Although our calculations were carried out for nearby lenses, the same considerations hold for other lenses as well, at least for a wide range of background fields. It is therefore clear that future monitoring programs, especially Pan-STARRS and LSST will be important sources of lensing data.

Afonso, C., et al. 2003, A&A, 404, 145
Afonso, C., et al. 2000, ApJ, 532, 340
Alard, C., & Lupton, R. H. 1998, ApJ, 503, 325
Alcock, C., et al. 2001, ApJ, 552, 259
Alcock, C., et al. 2001, ApJ, 562, 337
Alcock, C., et al. 2000, ApJ, 542, 281
Alcock, C., et al. 1998, ApJ, 499, L9 Alcock, C., et al. 1995, ApJ, 454, L125
Arnaboldi, M. 2003, Memorie della Societa Astronomica Italiana Supplement, 3, 184
Arnaboldi, M. et al. 2004, ApJ, 614, L33
Arzoumanian, Z. , Chernoff, D. F., & Cordes, J. M. 2002, ApJ, 568, 289A
Bailer-Jones, C. A. L., & Mundt, R. 2001, A&A, 367, 218
Beers, T. C., et al. 2004, IAU Symposium, 220, 195
Belokurov, V., et al. 2005, MNRAS, 357, 17
Burgasser A. J. 2001; The discovery and characterization of methane-bearing brown dwarfs and the definition of the T spectral class. PhD thesis. Calif. Inst. Technol. of 21E-3/pc3 for the T5-T8 range using 14 T dwarfs identified from 2MASS.
Caballero, J. A., Béjar, V. J. S., Rebolo, R., & Zapatero Osorio, M. R. 2004, A& A, 424, 857
Chambers, K. C., & Pan-STARRS 2004, American Astronomical Society Meeting Abstracts, 205,
Cruz K.L., Reid I.N., Liebert J., Kirkpatrick J.D., Lowrance P.J. 2003, Astron. J. 126:2421-48
Dahn, C.C. et al. 2002, AJ, 124, 1170
de Jong, J. T. A., et al. 2004, A& A, 417, 46
Di Stefano 2005a, *Binary Mesolenses*, in preparation
Di Stefano 2005b, *Lensing Tests for Supermassive Black Holes*, in preparation
Di Stefano & Kong 2005, *X-Ray Sources in the Halo of M31*, submitted.
Dominik, M., & Sahu, K. C. 2000, ApJ, 534, 213
Drake, A. J., Cook, K. H., & Keller, S. C. 2004, ApJL, 607, L29
Dyson, F.W., Eddington, A.S., & Davidson, C. 1920, Philos. Trans. R. Soc. London, A220, 291
Eddington, A. S., Jeans, J. H., Lodge, O. S., Larmor, J. S., Silberstein, L., Lindemann, F. A., & Jeffreys, H. 1919, MNRAS, 80, 96
Feldmeier, J. J. et al 2004a, ApJ, 615, 196
Feldmeier, J. J. 2004b, astro-ph/0407625
Freitag, M., Atakan Gürkan, M., & Rasio, F. A. 2005, astro-ph/0503130
Gates, E. I., Gyuk, G., & Turner, M. S. 1995, ApJ, 449, L123
Gaudi, S. & Bloom, J. 2005.
Gizis J.E., Monet D.G., Reid I.N., Kirkpatrick J.D., Liebert J., Williams R.J. 2000. Astron. J. 120:1085-99
Gould, A., Bennett, D. P., & Alves, D. R. 2004, ApJ, 614, 404
Gould, A. 2004, ApJ, 606, 319
Gould, A. 1996, ApJ, 470, 201
Griest, K. 1991, ApJ, 366, 412
Haberl, F. 2005, MPE Report Vol. 288, 39; astro-ph/0510480
Hogg, D. W., Quinlan, G. D., & Tremaine, S. 1991, AJ, 101, 2274
Holberg, J. B., Oswalt, T. D., & Sion, E. M. 2002, ApJ, 571, 512
Islam, R. R., Taylor, J. E., & Silk, J. 2004, MNRAS, 354, 629
Jiang, G., et al. 2004, ApJ, 617, 1307
Kirkpatrick J. D. 2001b; In Tetons 4: Galactic Structure, Stars and the Interstellar Medium, ed. CE Woodward, MD Bicay, JM Shull, ASP Conf. Ser. 231:17-35
Kirkpatrick, J. D. 2005, ARA&A, 43, 195
Kochanek, C. S. 2004, ApJ, 605, 58
Kaspi, V.M., Roberts, M.S.E., Harding, A.K. 2004, to appear in "Compact Stellar X-ray Sources", eds. W.H.G. Lewin and M. van der Klis, Cambridge University Press, astro-ph/0402136.
Kawka, A., Vennes, S., & Thorstensen, J. R. 2004, AJ, 127, 1702
Kerins, E., et al. 2003, ApJ, 598, 993
Kleinman, S. J., et al. 2004, ApJ, 607, 426
Knapp, G. R. 2002, Bulletin of the American Astronomical Society, 34, 1215
Liebert, J., Bergeron, P., & Holberg, J. B. 2005, ApJS, 156, 47
Luhman, K. L., Fazio, G., Megeath, T., Hartmann, L., & Calvet, N. 2005, Memorie della Societa Astronomica Italiana, 76, 285
Luhman, K. L. 2004, ApJ, 616, 1033
Luyten, W. J. 1999, VizieR Online Data Catalog, 3070, 0
McClintock, J.E. & Remillard, R.A. 2003, to appear in "Compact Stellar X-ray Sources," eds. W.H.G. Lewin and M. van der Klis, Cambridge University Press, astro-ph/0306213
McCook, G. P., & Sion, E. M. 1999, ApJS, 121, 1
Mao, S., et al. 2002, MNRAS, 329, 349
Mei, S., et al. 2005, ApJS, 156, 113
Miller, M. C., & Colbert, E. J. M. 2004, Int. J. Mod. Phys. D, 13, 1
Mohanty, S., Jayawardhana, R., & Basri, G. 2004, ApJ, 609, 885
Mushotzky, R. 2004, Progress of Theoretical Physics Supplement, 155, 27
Należyty, M., & Madej, J. 2004, A&A, 420, 507
Nguyen, H. T., Kallivayalil, N., Werner, M. W., Alcock, C., Patten, B. M., & Stern, D. 2004, ApJS, 154, 266
Okamura, S., et al. 2002, PASJ, 54, 883
Paczyński, B. 1996, ARAA, 34, 419
Paczyński, B. 1986, ApJ, 304, 1
Paulin-Henriksson, S., et al. 2003, A&A, 405, 15
Portegies Zwart, S. F., Baumgardt, H., Hut, P., Makino, J., & McMillan, S. L. W. 2004, Nature, 428, 724
Reid, I. N., Gizis, J. E., & Hawley, S. L. 2002, AJ, 124, 2721
Rockenfeller, B., Bailer-Jones, C. A. L., & Mundt, R. 2006, A& A, 448, 1111
Sakamoto, T., Chiba, M., & Beers, T. C. 2003, A&A, 397, 899
Saslaw, W. C., Narasimha, D., & Chitre, S. M. 1985, ApJ, 292, 348
Smith, M. C., Mao, S., & Woźniak, P. 2003, ApJ, 585, L65
Stubbs, C. W., Sweeney, D., Tyson, J. A., & LSST 2004, American Astronomical Society Meeting Abstracts, 205,
Tonry, J. L., & Schneider, D. P. 1988, AJ, 96, 807
Tully, R. B. 1988, Journal of the British Astronomical Association, 98, 316
Turner, E. L., Wardle, M. J., & Schneider, D. P. 1990, AJ, 100, 146
Udalski et al, 1994, Ap J 436, 103
Uglesich, R. R., Crotts, A. P. S., Baltz, E. A., de Jong, J., Boyle, R. P., & Corbally, C. J. 2004, ApJ, 612, 877
Volonteri, M., Madau, P., & Haardt, F. 2003, ApJ, 593, 661
Walsh, D., Carswell, R. F., & Weymann, R. J. 1979, Nature, 279, 381

Acknowledgements: I thank Ethan Vishniac, for discussions which encouraged me to split one long paper into this paper and its companion paper. I would also like to thank Tim Brown, Lorne Nelson, and Eric Pfahl for discussions, and John Tonry for providing relevant information. This work was supported in part by NAG5-10705 and in part by the National Science Foundation under Grant No. PHY99-07949.